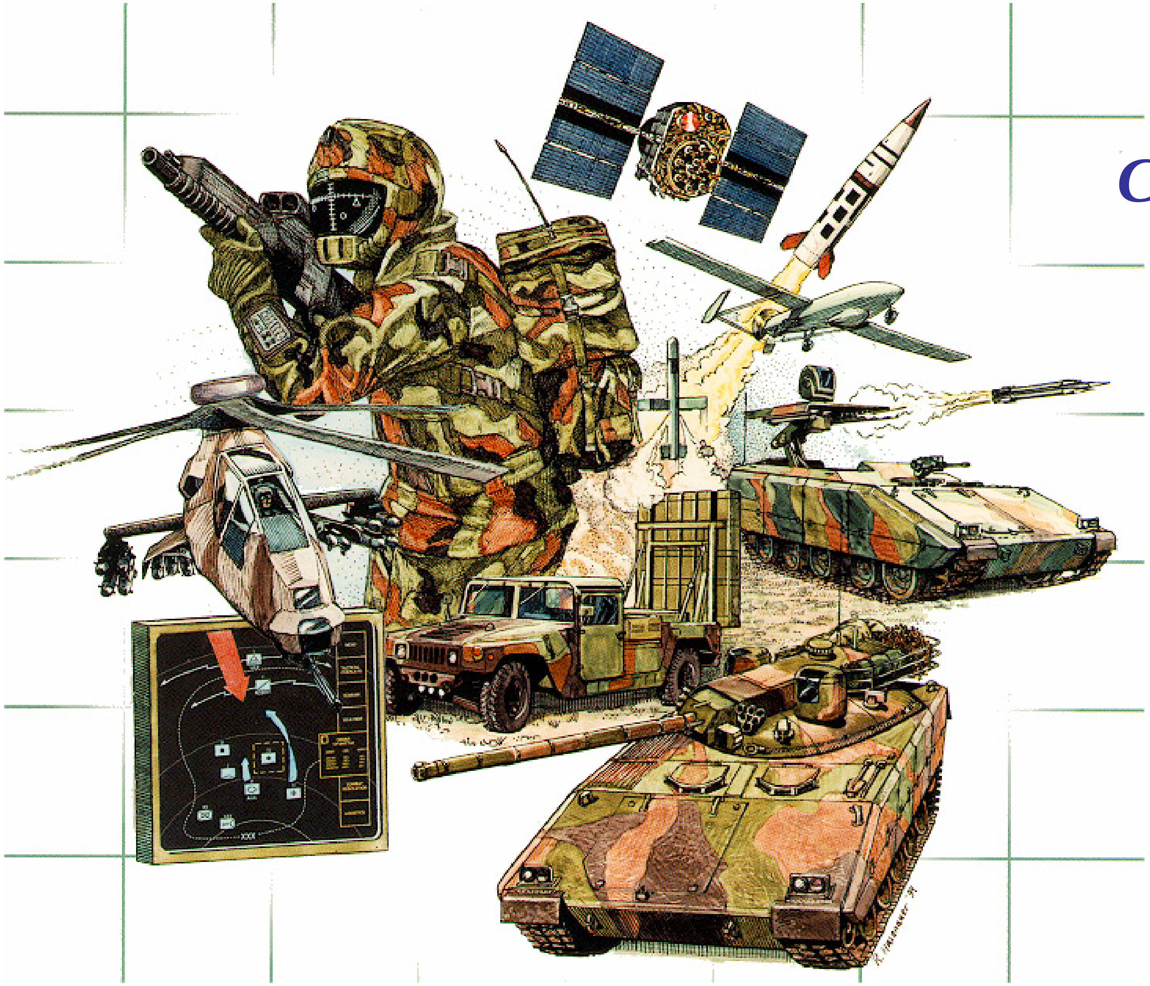
Fundamentals and Innovations Of Army Energy Conversion Systems



Symposium on Energy Conversion Fundamentals
Istanbul, Turkey
June 21-25, 2004

Dr. C. I. Chang
Director
US Army Research Office

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Outline

Overview of Army Basic Research

Challenges for Army Energy Conversion

Initiatives in Energy Conversion

- Compact Power
- Vehicle Propulsion
- Weapons Propulsion

Summary

Army Research Office

- **Director**
  - Legal Counsel
  - **Operations Directorate**
    - Support Management
    - Information Management
    - Acquisition Center
  - **Physical Sciences**
    - Physics
    - Chemical Sciences
    - Life Sciences
  - **Engineering Sciences**
    - Mechanical & Environmental Sciences
    - Materials Science
    - Electronics
    - URI Programs
  - **Mathematical & Information Sciences**
    - Mathematics
    - Computing & Information Sciences
    - Outreach Programs
    - Small Business Programs
    - International Research Offices

50 S&E PhD Program Managers

Provisional Organization Structure

Army Basic Research Pursuits

- Portable power
- Low power
- Intelligent
- Microsized
- Multifunctional
- Autonomous
- Lightweight
- Logistics ease

Communications & Information Processing Research
- Information fusion
- Wireless distributed communications
- MMW integrated devices

Mathematical Sciences
- Knowledge-based systems
- Intelligent systems
- Complex systems and control

Biological Sciences
- Microbiology & Biodegradation
- Physiology & Performance
- Nanoscale biomechanics

Chemical Sciences
- Electrochemistry
- Fast, energetic materials
- Dendritic polymers

Physics
- Image analysis
- Nanoscience
- Photonics

Mechanical Sciences
- "Smart" structures
- Rotorcraft aeromechanics
- Combustion/Propulsion

Materials Science
- Biomimetics
- Hierarchical materials
- Smart materials

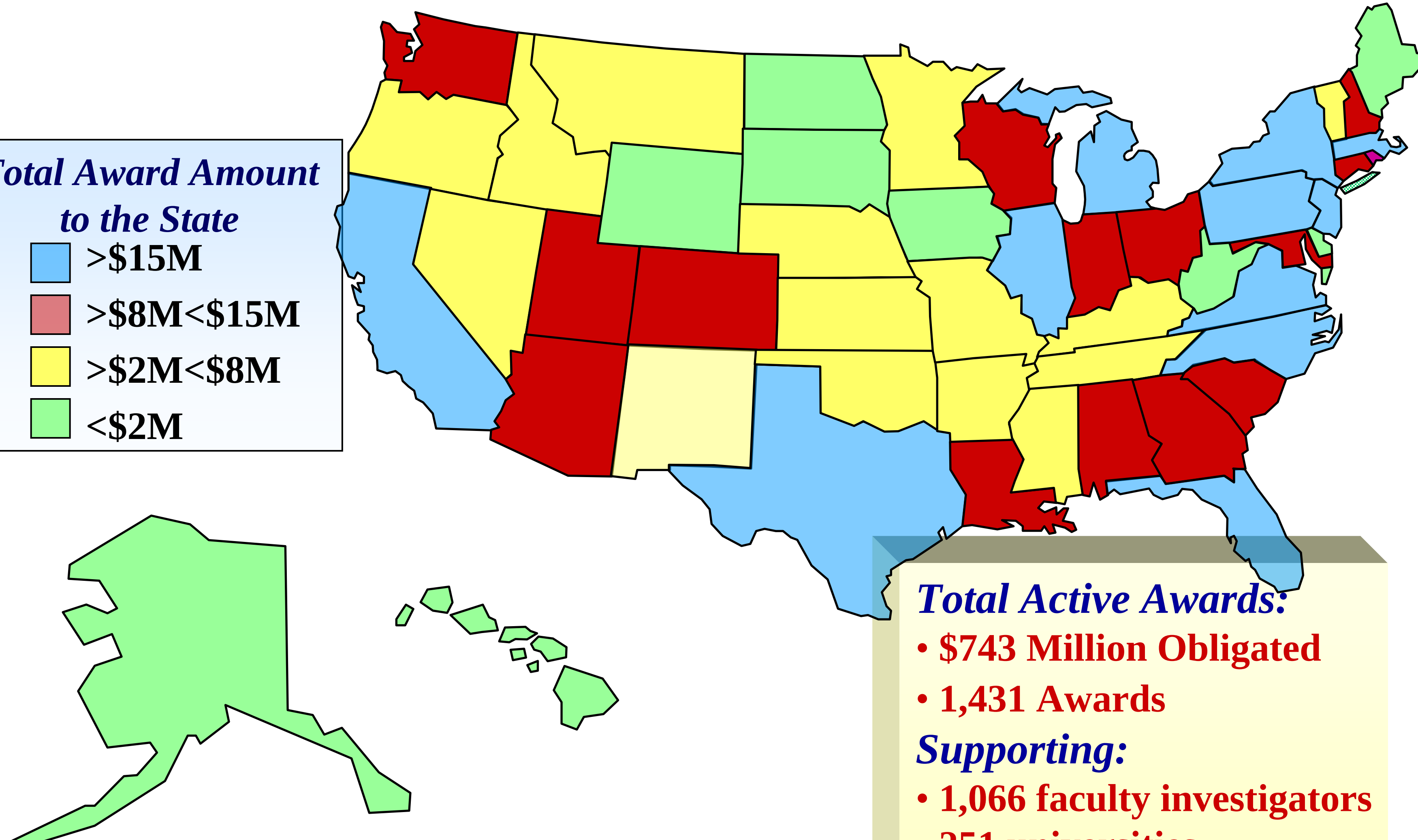
Atmospheric and Terrestrial Sciences
- Atmospheric aerosol transport
- Geomorphology
- Remote sensing

Electronics
- Low power/noise electronics
- Optoelectronic hybrids
- Quantum & High Frequency Electronics

Distribution of Research Funds Managed by ARO

Total Award Amount to the State

- >$15M
- >$8M<$15M
- >$2M<$8M
- <$2M



Total Active Awards:

- **$743 Million Obligated**
- **1,431 Awards**

Supporting:

- **1,066 faculty investigators**
- **251 universities**

As of May 2003

Challenges for Army Energy Conversion:

Mission Complexity

Force Transformation

Objective Force for Full Spectrum of Missions

Environmental Complexity

Urban

High

Open rolling terrain

Low

Increased strategic responsiveness

- ✓ Brigade in 96 hrs; Division in 120 hrs; Five Divisions in 30 days
- ✓ Fight immediately upon arrival
- ✓ Simultaneous air and sea lift
- ✓ Anti-terrorism

Stability and Support Operations

Small Scale Contingencies

Major Theater War

Spectrum of Conflict

Capabilities for an Uncertain Future:

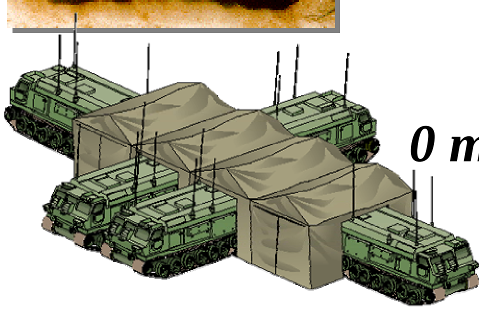
Current and future armies have a wider range of problems to solve

A Revolution in Capabilities
. . . Smaller, Lighter & Faster

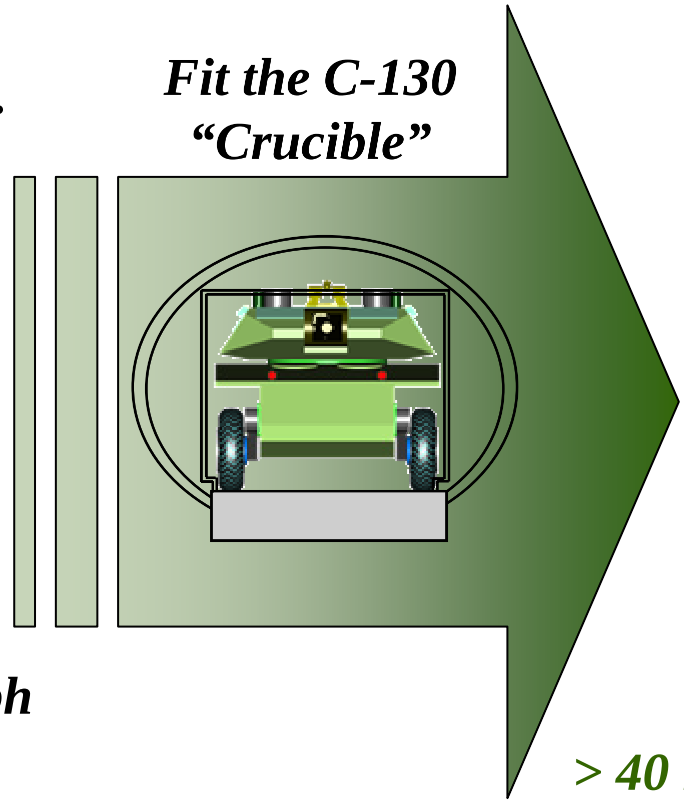
Today

~100 lb. load

70+ tons



0 mph



Objective Force

< 30 lb. effective load

< 20 tons

> 40 mph

Innovation -- Accelerating the Pace of Army Transformation

Compact Power for the Dismounted Soldier
Enabling the Future

Present
- heavy, single-purpose, non-integrated equipment

Future
- integrated, multi-functional protective suite

The Key is Lightweight, Compact Power

Specific Energy (Wh/kg)

SOURCE	SPECIFIC ENERGY (Theoretical)		SPECIFIC ENERGY (Practical)
Springs (watch)	0.25		0.15
Rechargeable Batteries	<1200		35-200
Primary Li/SO_2	1,400		175
Primary $Li/SOCl_2$	1,400		300
Zinc/air			300-400
TNT	1,400		N/A (M61 HG~260Wh)
Methanol	6,200		1,500-3,100
Ammonia	8,900	Energy	1,000-4,000
Carbon	9,100	of	2,000-4,000
Diesel (JP-8 similar)	13,200	Combustion	1,320-5,000
Hydrogen	33,000		1,000-17,000
Nuclear	2,800,000		190,000

ENERGY FROM COMBUSTION >> BATTERIES

Heat Engine vs Electrochemistry

Liquid Fuels
High Energy Density

Higher Temperature
Lower Efficiency
Minimal Fuel Processing
Can burn impurities
Good infrastructure
...

Combustion/Heat Engines

About 30-35% efficient (full power)

Lower Temperature
Higher Efficiency ?
Large Fuel Processor for many fuels (JP-8)
Sensitive to impurities
Little infrastructure
...

Electrochem/Fuel Cells

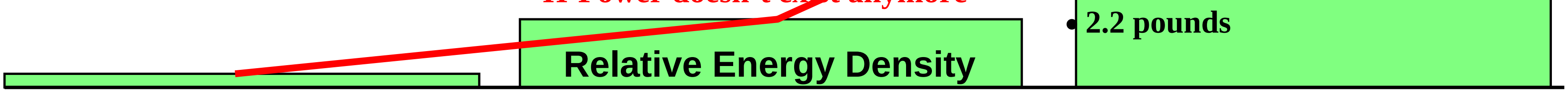
About 70% (reformer) X 50% (Fuel Cell) = 30-35% eff

Examples in H_2/Air fuel cell evolution

- **1992 - Analytic Power - SBIR:**
- **15 W (on a good day)**
- **No fuel included**
- **5 pounds**
- **Short life**
- **Analytic Power now produces much better stacks**

- **1996 - H-Power -DARPA/ARO:**
- **40 W sustained**
- **90 Wh of stored hydrogen**
- **3.5 pounds**
- **Starts/runs reliably after 6+ yrs**
- **Stack is used in commercial products**
- **H-Power doesn't exist anymore**

- **2001?- Ball Aerospace -**
- **PM Soldier? / DARPA / CECOM / ARO:**
- **Concept based on available technology**
- **15 W sustained, 25 W peak**
- **400 Wh of generated hydrogen in 1 pound fuel canister**
- **2.2 pounds**



The big challenge is the hydrogen fuel supply

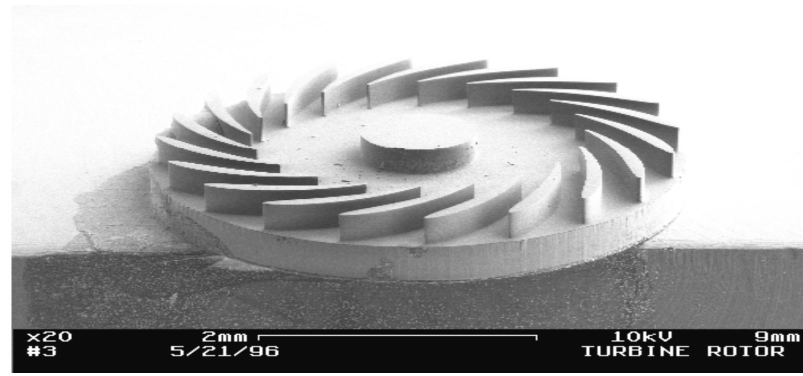
Microturbines

DoD funded Multidisciplinary University Research Initiative

Massachusetts Institute of Technology, Prof Alan Epstein and team of 45

Concept:

- μFab of refractory ceramics enables μheat engines (includes cooling units)
- Power densities approach those of full-sized engines
- Cost very low given sufficient demand
- μEngines enabling technology for few concepts



Payoff:

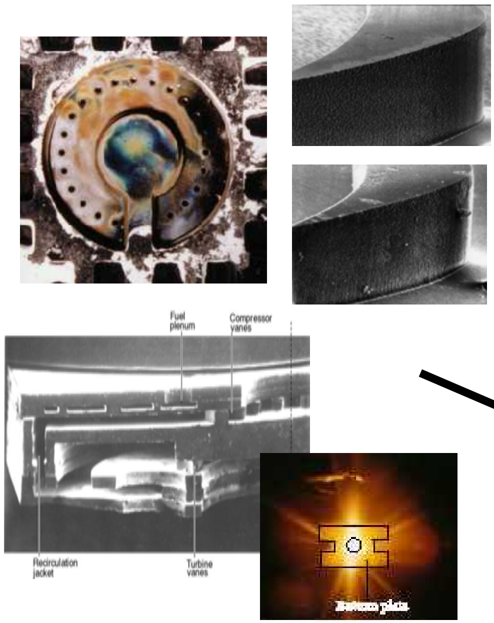
	μturbogen+fuel	BA5590
• Power	50 W	50 W
• Energy	175 W-hr	175 W-hr
• Weight	50 g	1000 g
• Size	50 cc	880 cc

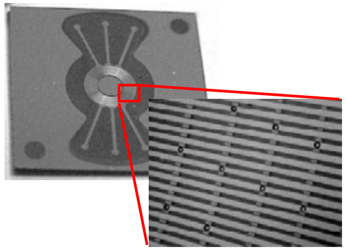
Accomplishments:

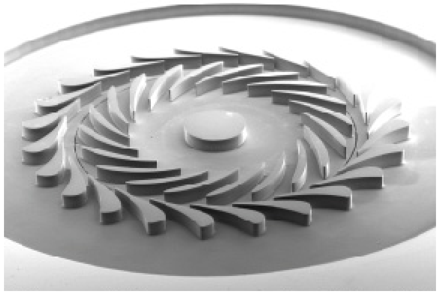
- Wafer scale fabrication demonstrated
- Cooled Si - high temp structural material
- Studies plus experiment suggests HC fuels can be burned in microcombustor
- Microbearings spun at 1.4M RPM
- 6-layer hot structures fabricated and tested

MURI/DARPA/ARL

MIT/ARO Demo Microturbine

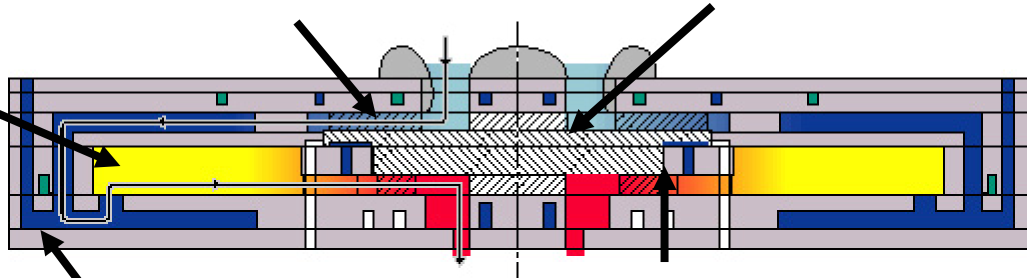




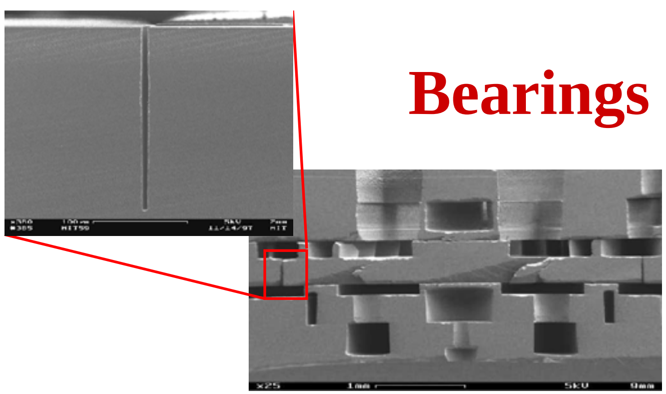


Motor/Generator

Turbomachinery



Combustion



Bearings

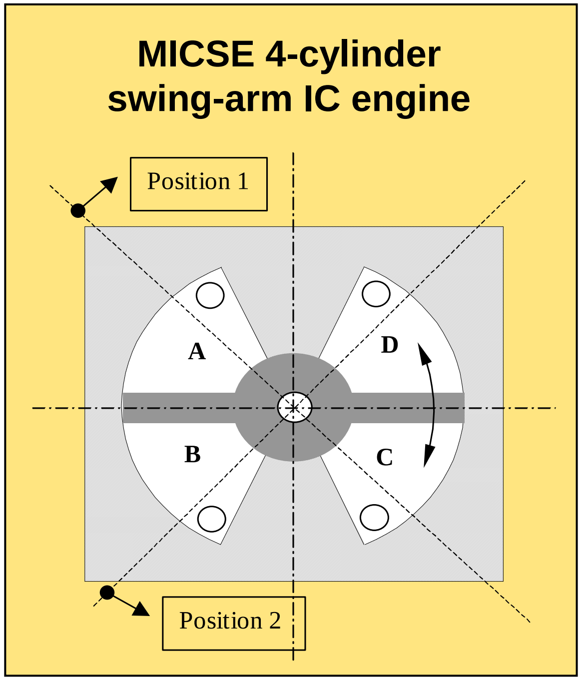
Electrical & Fluidic Interconnects

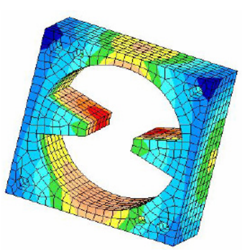
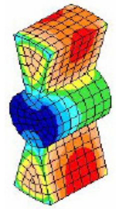
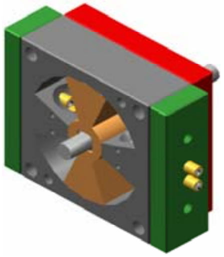
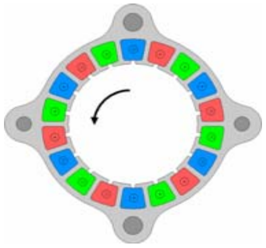
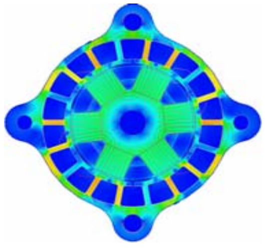
“Micro” Combustion Swing Engine

(Werner Dahm, wdahm@umich.edu)

- **Power generation systems based on small internal combustion engines with integrated generators:**
  - **Comparatively low fixed mass (high specific power)**
  - **Moderate thermal efficiencies (currently 8%; expected by end of program >17%)**
  - **Fuel flexible operation (butane/propane, JP-8,etc.)**

Micro Internal Combustion Swing Engine (MICSE)

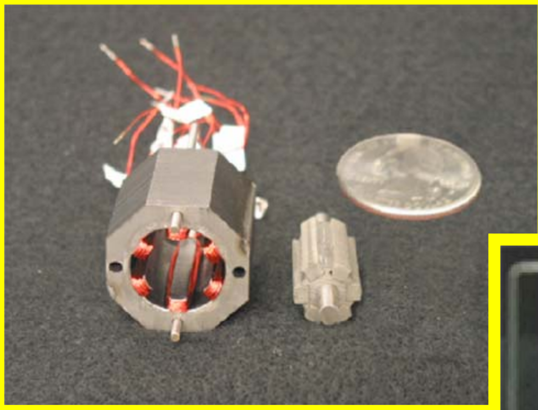


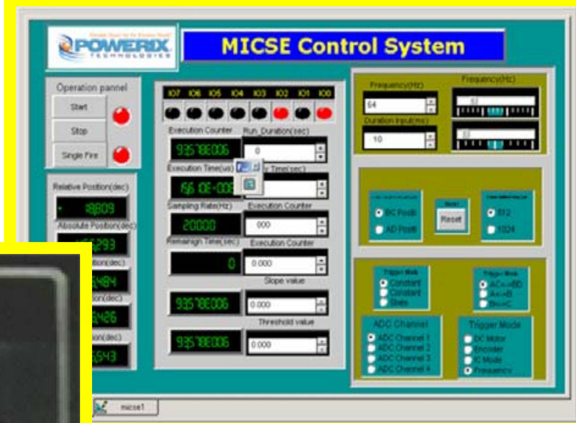

S.M. Wu Manufacturing Research Center
LTC Laboratory for Turbulence & Combustion
Portable Power for the Wireless World POWERIX TECHNOLOGIES
Mesoscopic Devices

Major Progress Areas

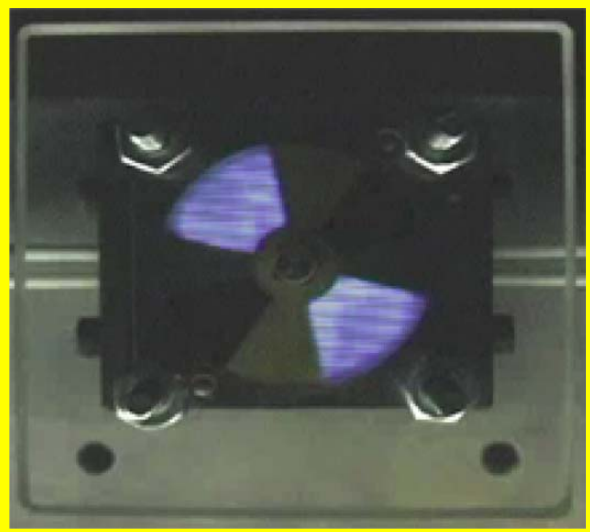
MICSE Generator Subsystem



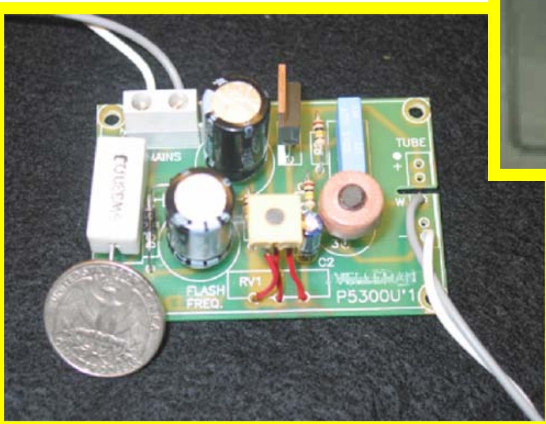
Engine Control Subsystem



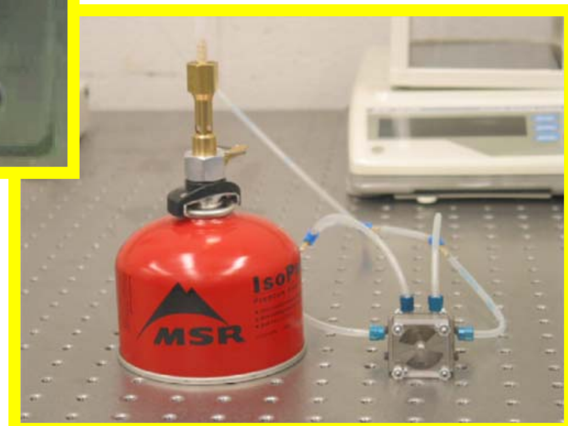
MICSE Engine Core



Ignition Subsystem



Fuel Subsystem



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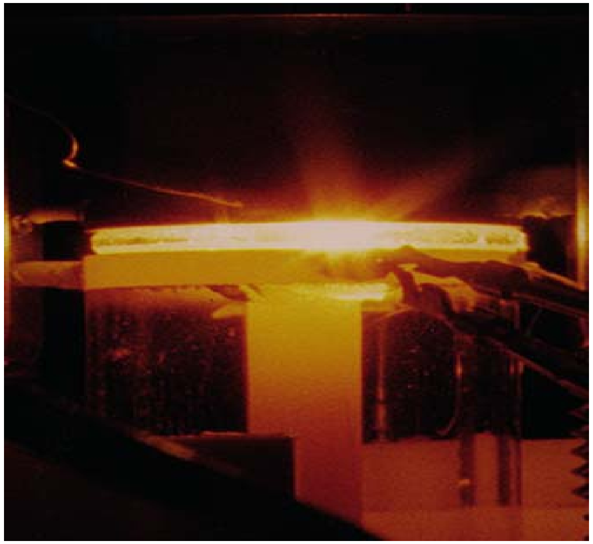
LTC Laboratory for Turbulence & Combustion

Portable Power for the Wireless World™ POWERIX TECHNOLOGIES

Mesoscopic Devices

Technical Challenges/Opportunities

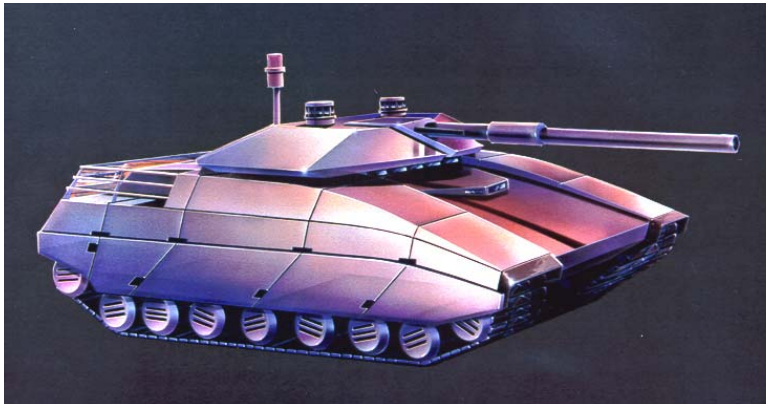
- **High-Temperature Materials**
  - Refractory material microfabrication (SiC, Si_3N_4, Al_2O_3, ???)
  - High temperature electrical properties for electromechanical components
- **Electromechanics:** decoupling of electrical and fluid performance
- **MEMS tribology:** very high speed bearings and drive trains, stiction
- **Fluid mechanics**
  - Diffusion at low Reynolds numbers
  - Flow turning with micro-fab constraints
- **Combustion:** Catalytic combustion of liquid fuels
- **Diagnostic tool development**
- **Wafer-Scale Precision Microfabrication**
- **Packaging of small high temperature systems**



200 W microcombustor operating at 1600°K

Vehicle Propulsion Research: Enabling the Army Transformation

M1 - Abrams Tank
70 tons



FCS Platform
20 tons

Future Combat System Drivers

Shrink the Logistics Burden

Typical Armored Division (6 x 4 x 2)*

Item	Number	Short Tons
Tracked vehicles	1,895	51,352
Trucks	3,031	23,913
Trailers	1,627	4,206
Aircraft	127	566
Equipment	--	5,600
Subtotal		85,637
30 day sustainment		104,970

* 17,000 personnel, TOE 87000J430, 6 armored battalions, 4 infantry battalions, 2 aviation battalions

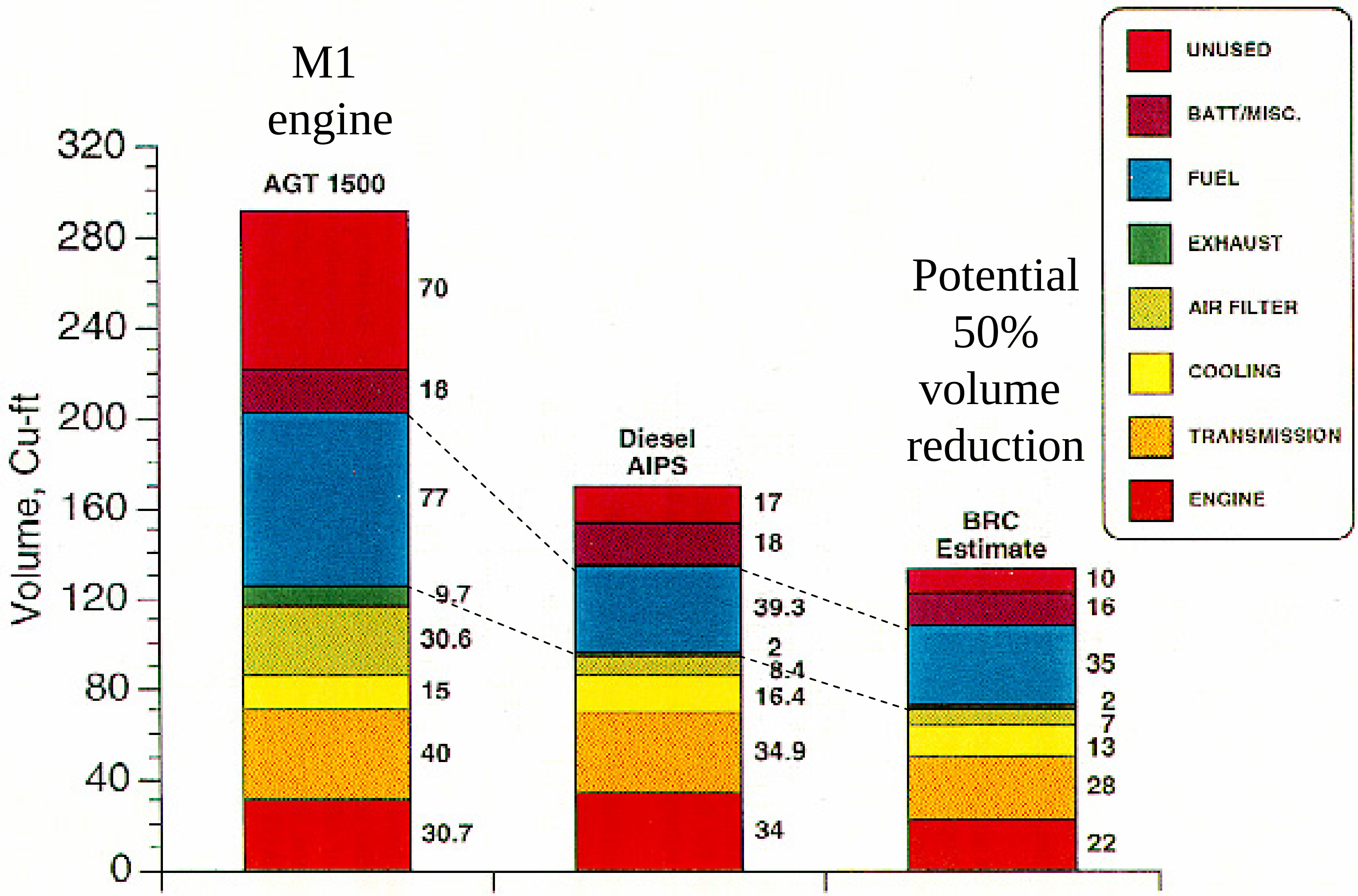
**** A heavy division consumes more than its own weight every 30 days***

*** 60% fuel, 30% ammo**

**** Combat vehicles are 56% of the weight and consume 73% of the fuel***

Propulsion System Analysis

- *the key to true high power density*



TACOM Blue Ribbon Study, November 1995

Figure 1-1. Volume reductions achievable by using high power density propulsion systems

Army Transformation for Future Army Propulsion

High Power Density

- Engine
  - High BMEP
  - Maximum air utilization
    - Near stoichiometric
    - High RPM
- System
  - Minimum propulsion system volume
    - Fuel, air handling, accessories

High Fuel Efficiency

- Low SFC engines
- Hybrid Systems

High Reliability

- Advanced diagnostics/prognostics

Reduced Logistics/Maintenance

Center of Excellence for Advanced Propulsion

- A Major Contribution -

The development of a validated computational capability for the analysis and design of reciprocating engines

Enhanced capabilities to analyze:

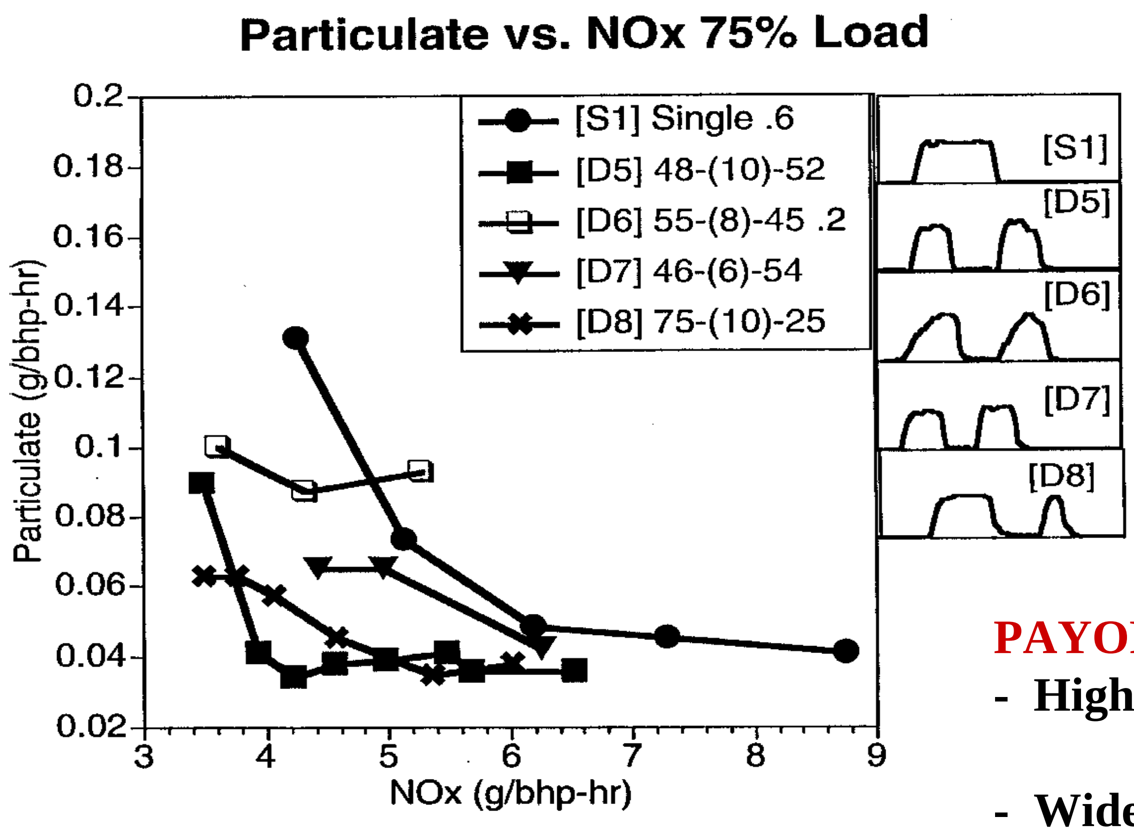
- **- Engine intake flow**
- **- In-cylinder turbulent flow**
- **- Fuel injection - injector -> nozzle -> spray**
- **- Liquid spray-wall interaction**
- **- Ignition/combustion dynamics**
- **- Pollutant formation/destruction**
- **- Heat transfer**

Which can then be used for model-based analysis of engine optimization and performance envelope determination

Fuel Injection Tailoring

Multi-Pulse Injection

Multi-Pulse Injection Results

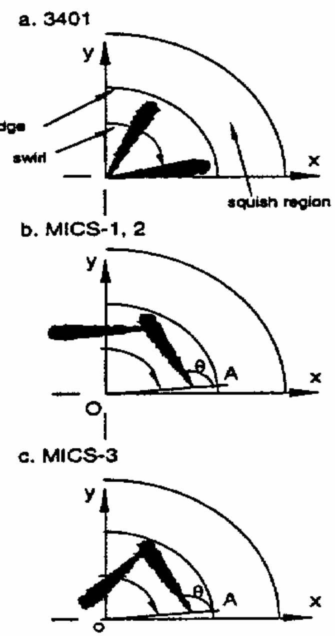


PAYOFF

- **High efficiency, Low emissions**

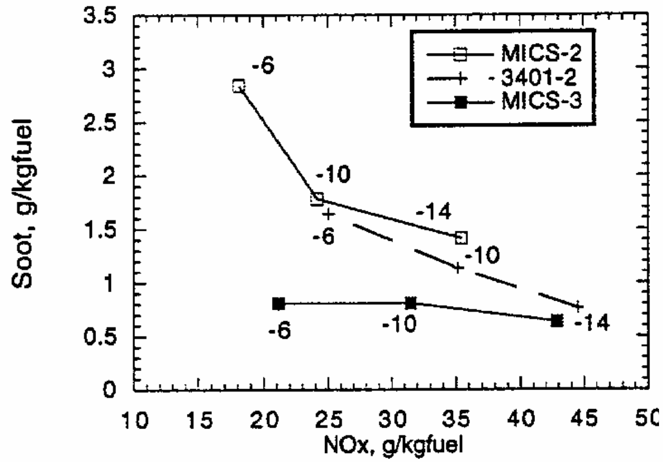
- **Wider range of engine operation**
  - -- **higher power density**
  - -- **lower, stable idle rpm**

Exploration of Strategies for High Power Density



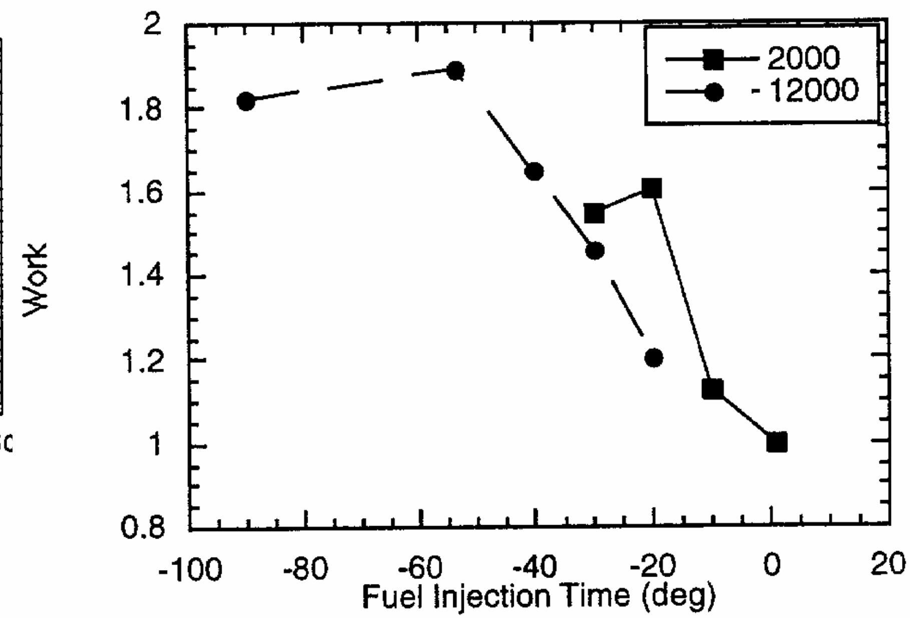
High Power Density

50% increased fueling rate



NOx and Soot with MICS-3 comparable to baseline engine at standard fueling rate

High RPM Operation



Analytical results guide selection of appropriate strategies

Weapons Propulsion

Nano-Scale Energetic Materials

6.1 Strategic Research Objective:

Insensitive High-Energy Materials

Characteristics

- Major research theme to achieve significant advancement

"Systems engineering" at the 6.1 level

- High payoff potential for future Army applications
- Stable, sustained investment for long-term (5-10 years) to achieve technology enablement

Advanced Energetic Materials

Coordinated through the National Advanced Energetics Program

Ranked in the top 5% of The Worlds Most Powerful Computing Sites

ENIAC Digital Computer
–BRL Ballistic Firing Tables

DOD High-Performance Computing – MSRC
Designer Energetic Materials & Full-Spectrum Modeling

ARL Nanoenergetics Program

Core and URI funded, WMRD and ARO collaboration

Program Thrusts

Novel Applications of Nanostructures to Propellants

Theoretical Analysis & Modeling

- Structure

- Reactivity/Sensitivity

High Rate Synthesis

- Plasma condensation, SolGel, Novel Structures, ?

Characterization

- In-situ, post-production

Nanoenergetics Initiatives

National Nanotechnology Initiative

- DURINT (Defense University Research Initiative in Nanotechnology)

- *Nano-Systems Energetics* (U. Minnesota)

Multidisciplinary University Research Initiative

- MURI 2004 - *Nanoengineered Energetic Materials* (Penn. State U. - start June 2004)

Conventional vs. Nanoscale Propellants

Combustion Characteristics of Conventional Propellants Governed by Characteristics of Composite Formulations:

- **Multi-scale, Multi-component: Particulates plus binder**
- **Particulate size distributions lead to local non-uniformity and clustering of smaller components**
- **Significant agglomeration of aluminum (if present) prior to ignition**
- **Rate of Reaction limited by species and thermal diffusivity**

A Novel Approach to Propellants Might Have:

- **Reduced size dispersion**
- **Greater uniformity**
- **Reduce agglomeration of aluminum**
- **Higher reaction rates**

A Radical Approach to Propellants Might Have:

- **Controllable energy release**

NANOSCALE ENERGETIC MATERIALS MAY BE THE PATHWAY TO ADVANCED ENERGETIC MATERIALS

Approaches to Nanoenergetics

1st Generation (pre 2000)

- Nanometer-sized Al powder/conventional propellants
  - Some performance gain, variable results

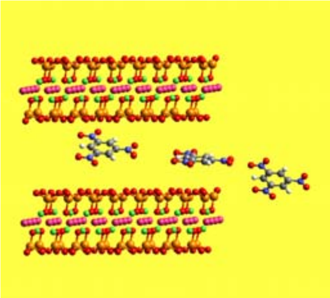
CL-20/NC Cryogel

(DURINT - Brill, U. Del.)

2nd Generation (current efforts)

- Coated nanometer-sized metal powders
  - Controlled oxidation, improved storage lifetime
- Quasi-ordered nanometer-sized inclusions in energetic matrix
  - Cryo-Gel/Sol-Gel processing

Self-Assembled Energetic Materials



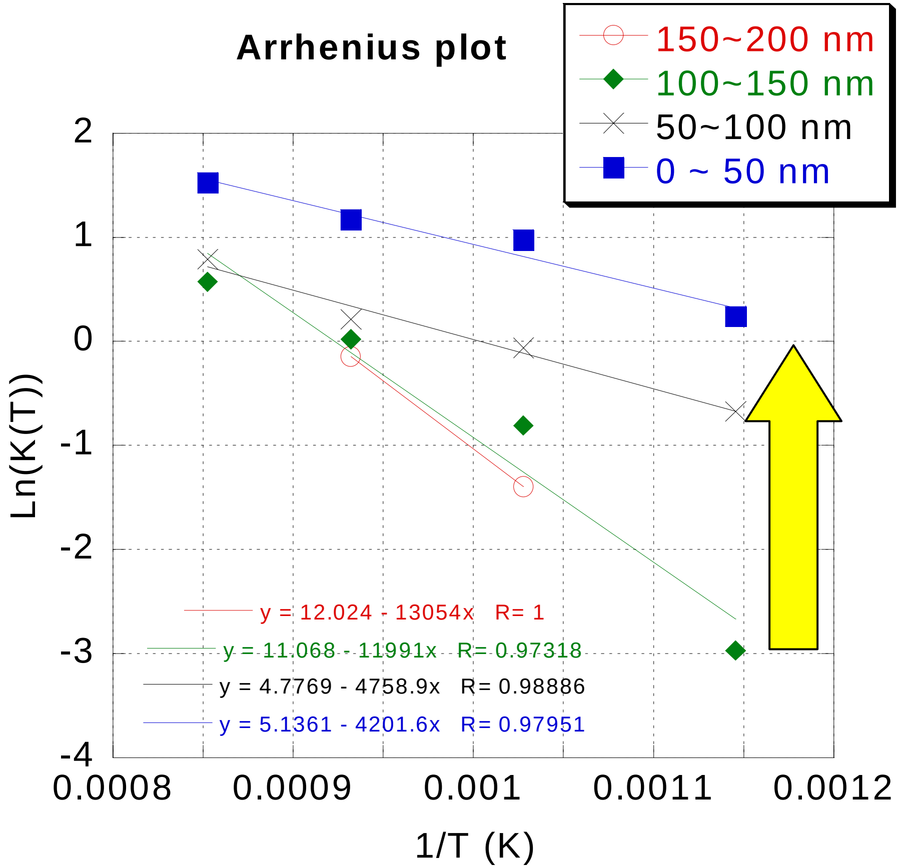
3rd Generation (new MURI program)

- 3-dimensional nanoenergetics
  - Structured/ordered
  - Controlled reactivity
  - Improved manufacturability/processing

Size-dependent Oxidation of Al Nanoparticles

DURINT - M. Zachariah, U. Maryland

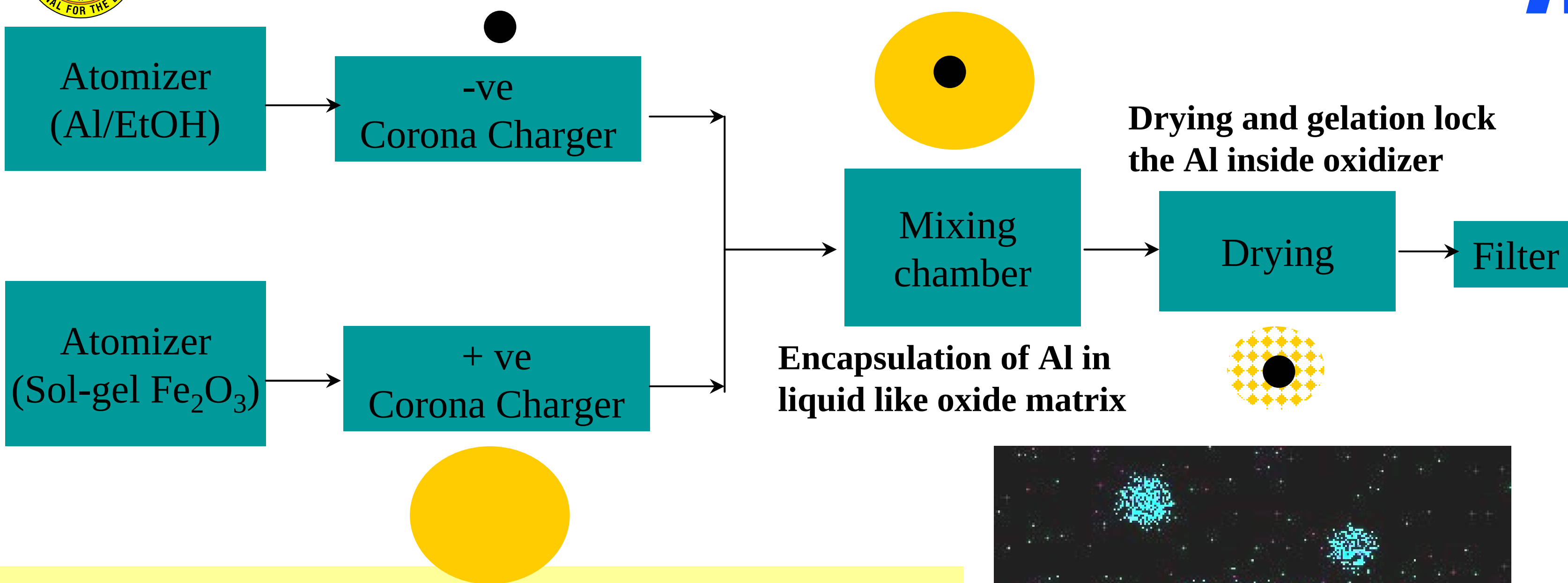
Particle produced in DC Plasma Discharge



First Measurement of Size Dependent Reaction Kinetics.

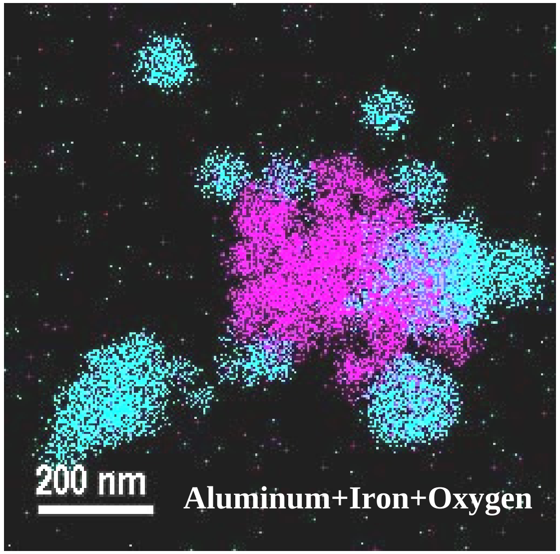
Encapsulation of Al in Fe_2O_3 matrix

DURINT - M. Zachariah, U. Maryland



Aerosol - plus - Sol Gel Chemistry for creation of novel Nanostructures

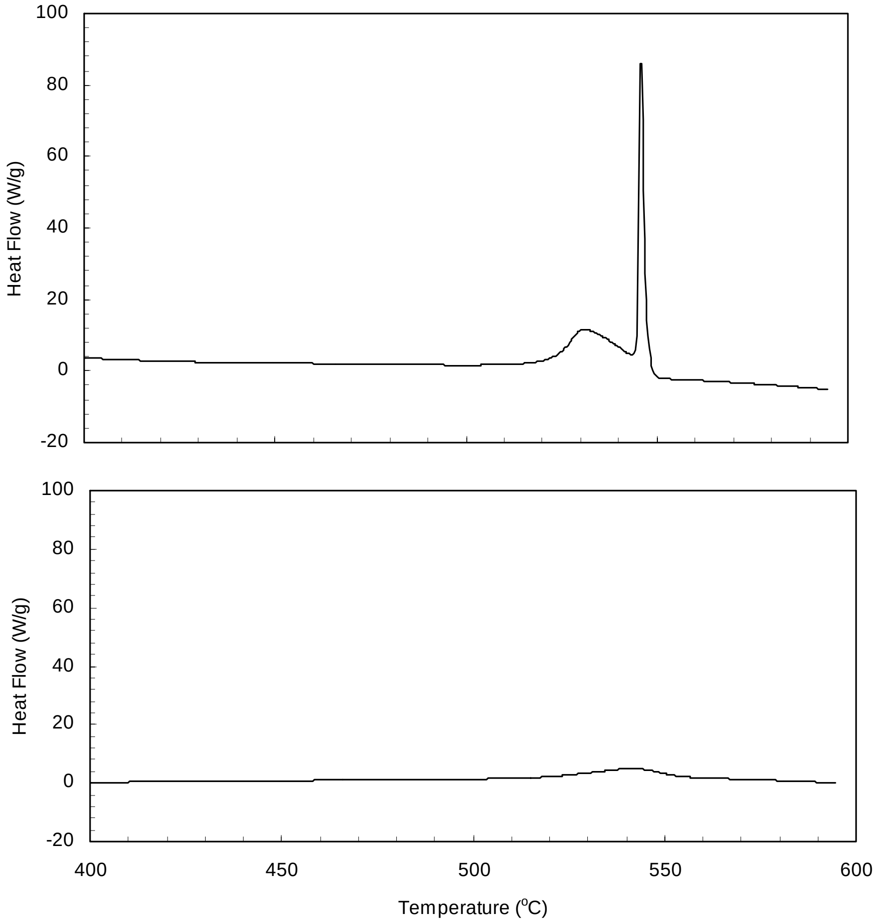
- Difficult to match time scales of drying and coagulation.
- Can not tell from TEM if Al is inside the oxidizer particle, because Al is lighter.
- STEM elemental map shows Al particle embedded in oxidizer

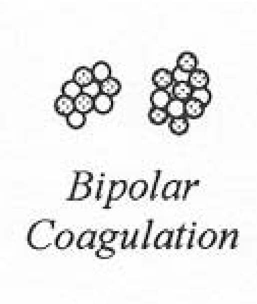


STEM elemental map of coagulated nanoparticle

Reactivity of Al in Fe_2O_3 matrix

DURINT - M. Zachariah, U. Maryland





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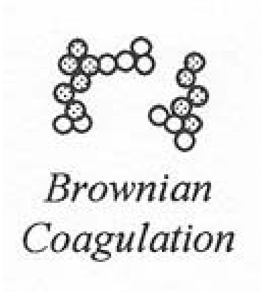

random

Ordered Nanoparticles Exhibit 10 X Energy Release Rate (Power)

Summary

Army research in energy conversion is addressing key challenges;

- Compact Power for the Dismounted Soldier
- High Performance/Efficiency Vehicle Propulsion
- Advanced Energetic Materials

Army research couples extramural academic and industrial programs with in-house capabilities

Army research is laying the foundation for the Army's future systems.